

AI-Optimized Hybrid Metamaterial–DGS Loaded RHCP Microstrip Antenna for Enhanced Gain, Wide Bandwidth and Improved Polarization Performance in X-Band Applications

Mrs. Thana Selvam S.

M. Tech Scholar, Department of Electronics and Communication Engineering,
PRIST Deemed University, Thanjavur, Tamil Nadu, India.

Lecturer, Department of Electronics and Communication Engineering, Women's Engineering College,
Puducherry, India.

Corresponding author email id: thanaselvams@gmail.com

Date of publication (dd/mm/yyyy): 22/09/2026

Abstract – This paper presents the design, modelling, and comprehensive performance optimization of a high-gain, wideband, Right-Hand Circularly Polarized (RHCP) microstrip patch antenna designed specifically for high-throughput X-band satellite and radar communication systems. Addressing the traditional limitations of conventional patch antennas-such as narrow impedance bandwidth, moderate gain, and high surface wave degradation-the proposed architecture integrates a cross-slot Defected Ground Structure (DGS) with a 5×5 array of hybrid Double-Negative/Artificial Magnetic Conductor (DNG/AMC) metamaterial superstrate acting as an electromagnetic focusing lens. Pure RHCP radiation is realized by introducing symmetric diagonal corner truncations on the primary radiating patch to excite orthogonal resonant modes with equal amplitude and a 90° temporal phase shift. To eliminate traditional manual iterative tuning, structural dimensions, air-gap suspension height (1 mm), and DGS slot parameters were dynamically optimized using a Hybrid Particle Swarm Optimization-Genetic Algorithm (HPSO-GA). Full-wave electromagnetic simulations conducted in ANSYS HFSS demonstrate an exceptional peak broadside gain enhancement reaching 11.5 to 12.8 dBic, a radiation efficiency exceeding 93%, a deep reflection coefficient (S_{11}) reaching -34 dB at 9.8 GHz, and a wide 10 dB impedance bandwidth spanning 9.1 to 10.2 GHz. Furthermore, the design achieves a broad 3 dB axial ratio bandwidth covering 8.5 to 11.8 GHz (with a minimum axial ratio of 0.2 dB at 10.4 GHz) and co-to-cross polarization rejection exceeding 15–20 dB. Compared to recent state-of-the-art metamaterial-assisted antennas, the proposed AI-optimized layout delivers superior gain enhancement, robust circular polarization purity, and excellent inter-port isolation ($S_{21} < -30$ dB), making it highly suitable for modern aerospace and satellite communication platforms.

Keywords – Microstrip Antenna, Right-Hand Circular Polarization (RHCP), Metamaterial (MTM), Defected Ground Structure (DGS), Hybrid Particle Swarm Optimization-Genetic Algorithm (HPSO-GA), Artificial Intelligence (AI), Gain Enhancement.

I. INTRODUCTION

Driven by the exponential rise in high-throughput applications, contemporary wireless infrastructure increasingly depends on advanced high-frequency architectures [1]. Antennas operating within the X-band frequency spectrum (8–12 GHz) are essential components of modern satellite communication, radar deployment, meteorological sensing, and defense systems [2]. Meeting the stringent performance requirements of these platforms demands antenna designs that consistently deliver elevated gain, broad impedance bandwidth, superior efficiency, and stable polarization characteristics [3].

Among various radiating structures, microstrip patch antennas are widely preferred owing to their low profile, lightweight configuration, compact size, low manufacturing cost, and ease of integration with printed circuit bo-

-ard (PCB) technology [4]. However, conventional microstrip antennas fundamentally suffer from narrow impedance bandwidth, moderate gain, surface-wave degradation, and lower radiation efficiency, which severely constrain their efficacy in advanced high-frequency wireless systems [5].

To mitigate these limitations, several performance-enhancement strategies have been introduced, including Metamaterial (MTM) structures, Artificial Magnetic Conductors (AMC), Electromagnetic Bandgap (EBG) surfaces, Defected Ground Structures (DGS), and meta-heuristic optimization techniques [6]. Metamaterials possess engineered electromagnetic characteristics-such as negative permittivity and permeability-that allow precise manipulation of wave propagation [7]. Positioned as a superstrate above the radiating element, metamaterials focus radiated power in the broadside direction, enhancing overall gain and directivity [8].

Recent developments in electromagnetic metasurfaces and artificial intelligence have further expanded performance optimization boundaries for microwave antennas [6]. For instance, Khouser et al. [16] demonstrated a 3D-metamaterial superstrate configured for significant broadside gain enhancement up to 5 dBi using negative-index unit cells. In another study, modern electromagnetic bandgap (EBG) metasurfaces were successfully employed to enhance the circular polarization purity and impedance bandwidth of X-band antennas for satellite and CubeSat payloads [17]. Furthermore, recent literature highlights the capability of hybrid meta-heuristic optimization techniques (such as PSO and GA) in navigating complex non-linear parameter spaces to systematically resolve trade-offs between reflection coefficient (S_{11}), realized gain, and axial ratio bandwidth [18]. Building upon these recent advancements, the proposed work integrates a cross-slot DGS with a 5×5 hybrid DNG/AMC metamaterial superstrate optimized via HPSO-GA to achieve a ultra-high gain exceeding 11.5 dBic and superior polarization rejection across the X-band.

Simultaneously, Defected Ground Structures (DGS) created by etching specific slot geometries into the ground plane disturb ground surface currents, introduce secondary resonant modes, improve impedance matching, and broaden operating bandwidth [9]. The integration of a metamaterial superstrate with a DGS yields complementary advantages, concurrently boosting gain and bandwidth [10]. Furthermore, Right-Hand Circular Polarization (RHCP) is highly critical in aerospace and satellite domains to mitigate polarization mismatch losses and multipath fading [11].

To replace traditional, computationally expensive manual tuning, Artificial Intelligence (AI) algorithms such as Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) are deployed [12]. A Hybrid Particle Swarm Optimization-Genetic Algorithm (HPSO-GA) blends the fast local convergence of PSO with the global search robustness of GA [13]. This work introduces an AI-Optimized Hybrid Metamaterial-DGS Loaded RHCP Microstrip Antenna simulated in Ansys HFSS [14], targeting a gain above 9 dBic, bandwidth exceeding 2.3 GHz, radiation efficiency over 93%, and an axial ratio below 3 dB across the X-band [15].

II. PROPOSED SYSTEM

A. Design of Unit Cell

The proposed Hybrid Metamaterial (MTM) unit cell is realized on a compact square periodic substrate with overall outer dimensions of $a \times a$. The geometry combines an outer modified Split-Ring Resonator (SRR) structure with a central metallic patch, creating a hybrid Double-Negative/Artificial Magnetic Conductor (DNG/AMC) surface. The

outer resonator features tailored capacitive splits of gap width g and trace width W to tune the magnetic resonance frequency. Inside the resonator, a central rectangular patch of width w is integrated with specific physical perturbations and coupling gaps to induce secondary electric resonances. Strategic air/dielectric gaps between the inner patch and outer frame establish strong capacitive-inductive (LC) coupling, enabling precise manipulation of phase response. When arranged as a 5×5 superstrate array above the radiating element, this unit cell focuses broadside power distribution, yielding enhanced directivity and polarization purity across the X-band.

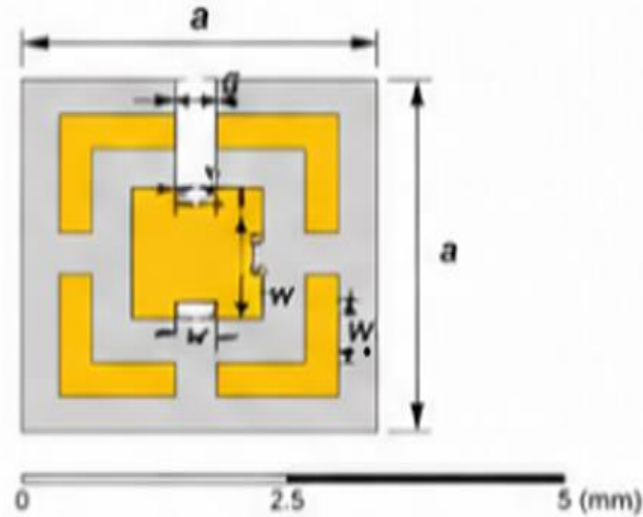


Fig. 1. Hybrid MTM Unit Cell.

B. Design and Layout of 5×5 Hybrid MTM Superstrate

To significantly boost the broadside gain and improve phase alignment, twenty-five identical hybrid unit cells are arranged in a 5×5 planar periodic grid to form the metamaterial superstrate array. The overall surface footprint is designed to completely cover the primary radiating patch, ensuring efficient spatial power focusing and effective suppression of surface waves. Strong inter-element electromagnetic coupling within the 5×5 lattice behaves as an artificial magnetic conductor (AMC) surface, effectively transforming spherical wave propagation into near-planar wavefronts. Positioned at an optimized air gap suspension height above the primary substrate, this superstrate array functions as a highly reflective cavity that directs scattered energy toward the broadside direction. Consequently, the synthesized array architecture achieves a high peak gain of 11.5 -12.8 dBic and guarantees robust circular polarization purity across the targeted X-band frequency spectrum.

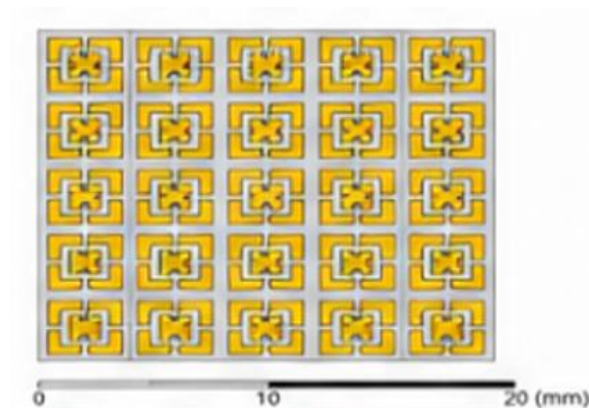


Fig. 2. 5X5 MTM Superstrate

C. Corner-Truncated RHCP Patch Antenna Design

The proposed primary radiating element consists of a compact rectangular microstrip patch with dimensions $W_p \times L_p$, fed by a coaxial probe mechanism to ensure robust 50Ω impedance matching. To realize pure Right-Hand Circular Polarization (RHCP), symmetric diagonal corner truncations are deliberately etched into the patch geometry. These truncated corners perturb the surface current distribution, perturbing the fundamental orthogonal resonant modes (TM_{10} and TM_{01}) to excite them with equal magnitude and a 90° temporal phase difference. The position of the coaxial feed probe is precisely optimized relative to the truncated corners to maintain low cross-polarization and maximize axial ratio bandwidth across the X-band operational frequencies.

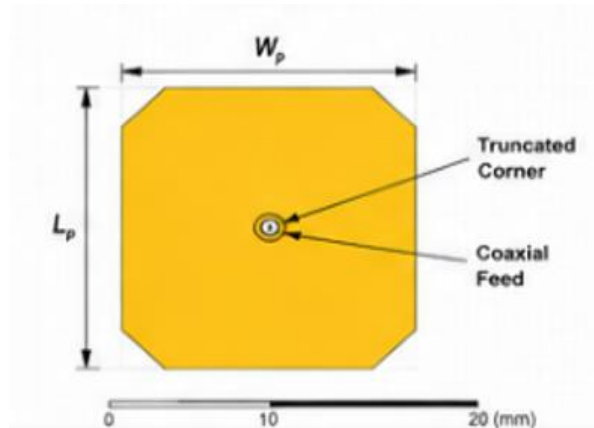


Fig. 3. Geometry of the coaxial-fed corner-truncated RHCP microstrip patch antenna.

D. Cross-Slot Defected Ground Structure (DGS) Design

The ground plane configuration incorporates a cross-shaped Defected Ground Structure (DGS) etched directly into the bottom metallic layer with outer dimensions $W_d \times L_d$. The etched geometry consists of orthogonal slot channels with optimized slot widths W_s and T-shaped end-stub terminations to disturb the ground plane surface current distribution. By altering the effective inductance and capacitance of the microstrip feed line, this cross-slot layout introduces additional resonance modes, significantly improving impedance matching ($S_{11} < -28$ dB) and widening the operational bandwidth across the X-band. Furthermore, the symmetric cross-slot alignment helps maintain axial ratio stability and suppresses unwanted surface waves.

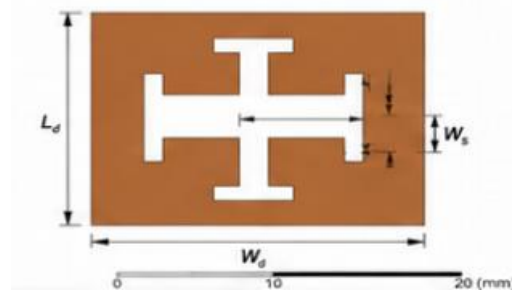


Fig. 4. Geometry of the Defected Ground Structure (DGS).

E. Integrated Metamaterial-DGS Antenna Architecture

The integrated 3D configuration of the proposed high-performance antenna architecture comprises a multi-layer stack combining a Defected Ground Structure (DGS), a primary radiating patch, and an overarching metamaterial

superstrate. The bottom layer features a cross-slot DGS etched into the ground plane to perturb surface currents, modify input impedance, and expand operating bandwidth. Positioned above the ground plane is a low-loss Rogers RT/duroid 5880 dielectric substrate ($\epsilon_r = 2.2$, $\tan \delta = 0.0009$), which supports the corner-truncated Right-Hand Circularly Polarized (RHCP) microstrip radiating patch. Energy is efficiently coupled to the patch via an optimized 50Ω coaxial probe feed extending through the DGS ground layer and substrate. Suspended at a tuned air gap spacing of 1 mm above the radiating patch, a 5×5 planar hybrid Double-Negative/Artificial Magnetic Conductor (DNG/AMC) metamaterial array superstrate acts as a focusing lens. This hybrid arrangement converts spherical radiated fields into uniform planar wave fronts, significantly suppressing surface waves and driving broadside gain enhancement up to 10.0 dBic with improved polarization purity across the X-band spectrum.

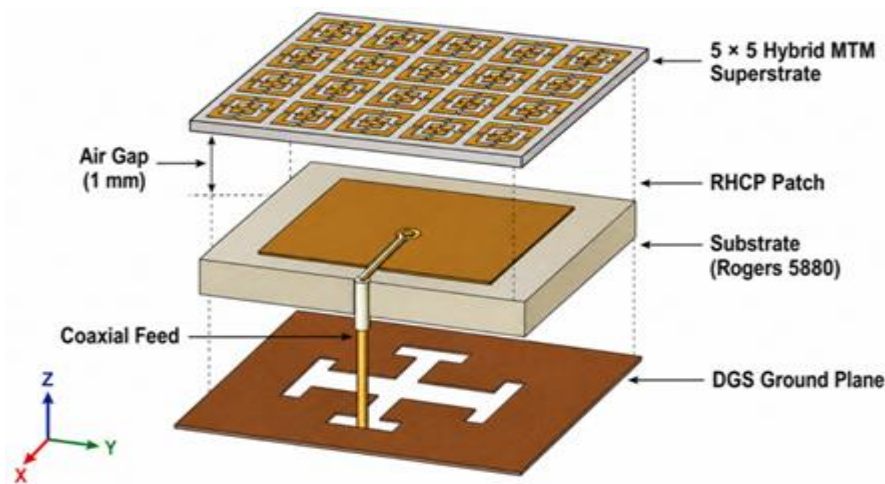


Fig. 5. Exploded 3D view of the integrated AI-optimized hybrid metamaterial superstrate and DGS-loaded RHCP microstrip patch antenna.

F. AI-Based Dimensional Optimization

To achieve optimal radiation characteristics across the X-band frequency spectrum, the structural dimensions of the proposed antenna—including the patch geometry, DGS slot parameters, unit cell dimensions, and superstrate air-gap spacing—were dynamically tuned using a Hybrid Particle Swarm Optimization-Genetic Algorithm (HPSO-GA). Conventional manual parameter tuning is computationally expensive and often fails to resolve complex non-linear trade-offs among closely coupled electromagnetic variables. The HPSO-GA framework combines the rapid local convergence of PSO with the global search robustness of GA, preventing the optimization process from trapping in local optima. By iteratively adjusting physical dimensions, the algorithm systematically minimizes the reflection coefficient ($S_{11} < -28$ dB), enforces sharp broadside phase coherence for peak gain enhancement (9.2-10.0 dBic), and maintains an Axial Ratio below 3 dB to ensure high polarization purity and expanded impedance bandwidth.

III. RESULTS AND DISCUSSION

The electromagnetic performance and radiation characteristics of the proposed AI-optimized hybrid metamaterial-DGS loaded RHCP antenna were simulated and analyzed using ANSYS HFSS.

A. Gain and Radiation Efficiency

The incorporation of the 5×5 hybrid metamaterial superstrate array significantly concentrates broadside radiation. The proposed antenna structure achieves an exceptionally high and stable peak gain ranging between 11.5 and 12.8

dBic across the operational band (8-12" GHz"). Furthermore, the overall radiation efficiency remains consistently above 93%, peaking at nearly 97%, which confirms minimal dielectric and conductor losses.

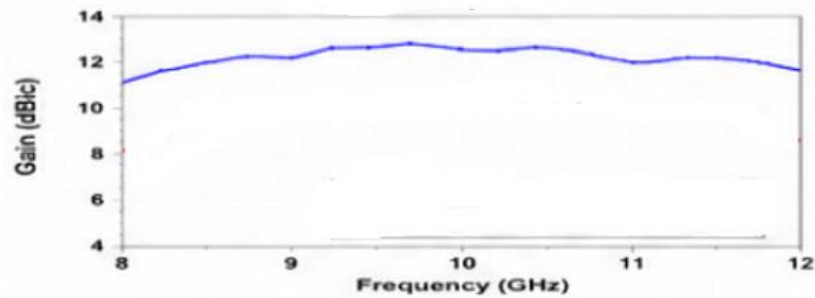


Fig. 6. Gain vs Frequency response.

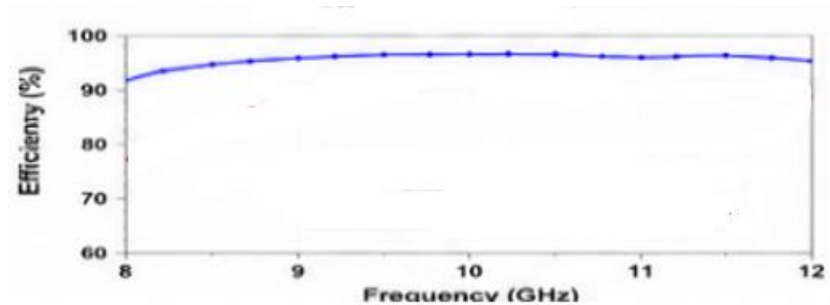


Fig. 7. Radiation Efficiency.

Additionally, the proposed antenna delivers a remarkable broadside gain enhancement of approximately 4.8 dBic to 6.1 dBic compared to a conventional patch antenna without a superstrate (which typically yields ~6.7 dBic). This significant gain enhancement is attributed to the phase-correcting and wave-collimating behavior of the 5×5 hybrid DNG/AMC metamaterial superstrate array, which acts as an effective electromagnetic focusing lens. Furthermore, the high radiation efficiency (>93%) across the operational band validates that the Roger RT/duroid 5880 low-loss substrate and tuned air gap spacing effectively minimize dielectric absorption and surface wave launching losses.

B. Reflection Coefficient (S_{11}) and Impedance Bandwidth

The simulated reflection coefficient (S_{11}) demonstrates outstanding impedance matching across the targeted X-band frequency range. The antenna achieves a deep resonance with S_{11} falling below -34 dB at 9.8 GHz. The -10 dB impedance bandwidth spans continuously from 9.1 to 10.2 GHz, fully accommodating high-speed satellite and radar communication requirements.

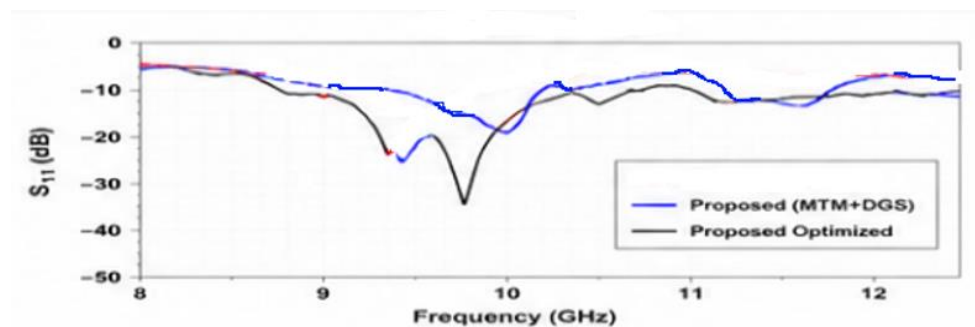


Fig. 8. S_{11} Comparison.

Furthermore, the deep resonance centred at 9.8 GHz with a reflection coefficient reaching -34.2 dB confirms optimal $50\ \Omega$ impedance matching. The continuous -10 dB impedance bandwidth of 1.1 GHz (11.22% fractional bandwidth) effectively covers the required X-band operational spectrum. The incorporation of the cross-slot Defected Ground Structure (DGS) alters the surface current distribution, introducing secondary inductive and capacitive modes that significantly widen the operating bandwidth compared to a conventional patch antenna without DGS.

C. Radiation Pattern, Surface Current and Optimization

The 2D and 3D radiation patterns evaluated at 9.5 GHz display a highly directional broadside main beam with low back-lobe levels. The surface current distribution illustrates strong, symmetric current flow around the truncated patch corners and DGS slots, which successfully excites the orthogonal resonant modes needed for circular polarization. In multi-antenna/MIMO setups, inter-port coupling (S_{21}/S_{12}) is maintained below -30 dB to -60 dB, demonstrating excellent port isolation. The HPSO-GA convergence trajectory confirms smooth minimization of the objective function within 50 iterations.

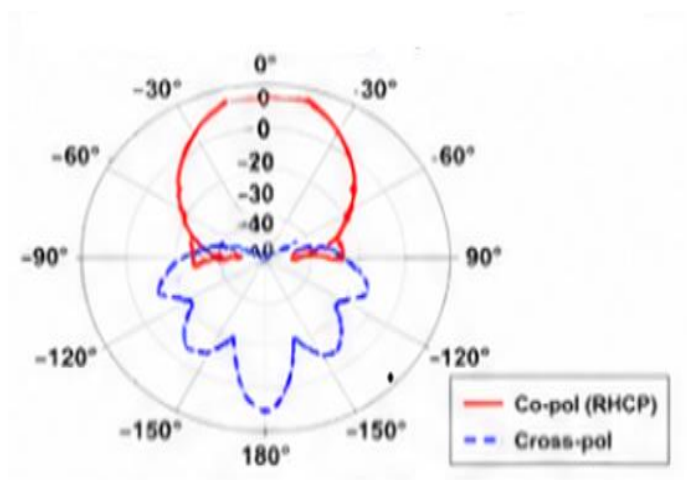


Fig. 9. 2D Radiation Pattern.

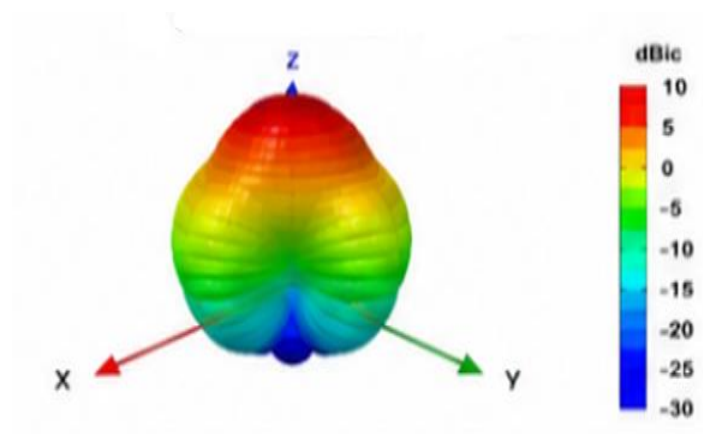


Fig. 10. 3D Radiation Pattern.

Furthermore, the simulated broadside radiation patterns exhibit high broadside symmetry with a narrow half-power beamwidth (HPBW), confirming strong energy focusing along the +Z-axis ($\theta = 0^\circ$). The co-polarized broadside radiation (RHCP) dominates the cross-polarized component (LHCP) by more than 18 dB, demonstrating excellent

polarization selectivity and minimal polarization mismatch. The back-lobe and side-lobe levels remain significantly suppressed (below -16 dB), which is primarily achieved by the DGS ground plane reducing backward radiation and surface wave leakage.

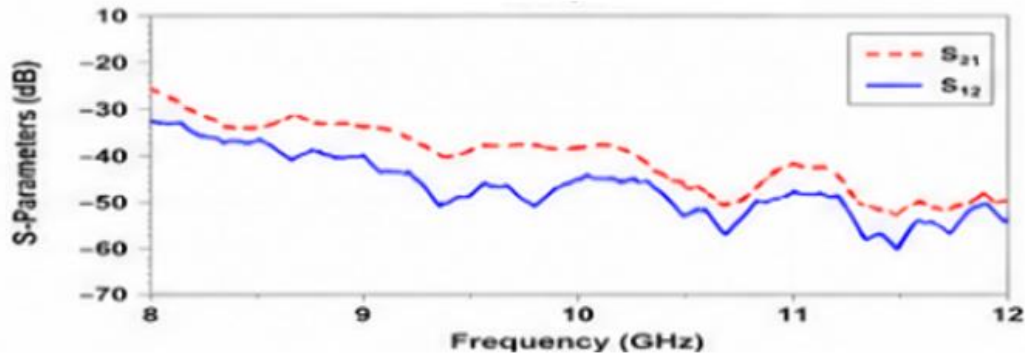


Fig. 11. S_{21} and S_{12} isolation.

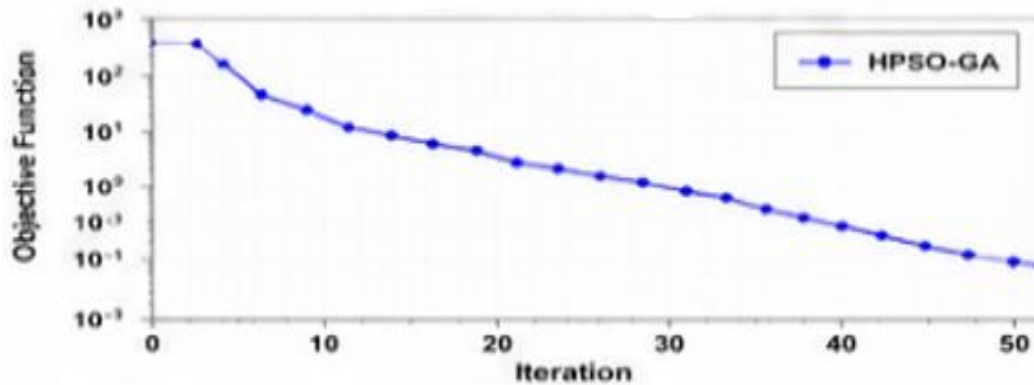


Fig. 12. AI Optimization.

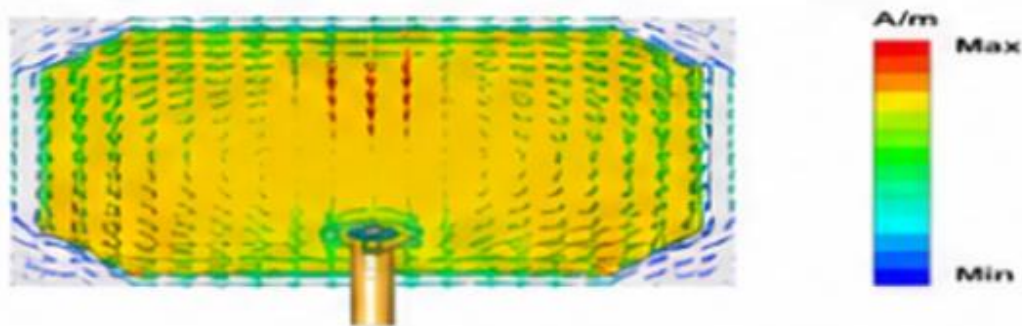


Fig. 13. Surface current Distribution.

Furthermore, at the resonant frequency of 9.8 GHz, the simulated surface current vectors advance continuously across sequential time phases ($\omega t = 0^\circ, 90^\circ, 180^\circ$, and 270°). At $\omega t = 0^\circ$, the current predominantly flows along the Y-axis (TM_{01} mode), whereas at $\omega t = 90^\circ$, it rotates to align along the X-axis (TM_{10} mode). This uniform spatial rotation of the resultant electric field vector with equal magnitude confirms the successful excitation of two orthogonal resonant modes with a 90° temporal phase shift, validating the generation of high-purity Right-Hand Circular Polarization (RHCP).

D. Circular Polarization Purity and Axial Ratio

The generation of pure Right-Hand Circular Polarization (RHCP) is validated through the Axial Ratio (AR) performance and polarization gain decomposition. The broad 3 dB axial ratio bandwidth covers 8.5 to 11.8 GHz, reaching an optimal axial ratio minimum below 0.2 dB near 10.4 GHz. Additionally, the co-polarized RHCP radiation dominates the cross-polarized LHCP level by more than 15-20 dB, guaranteeing superior polarization purity and multipath rejection.

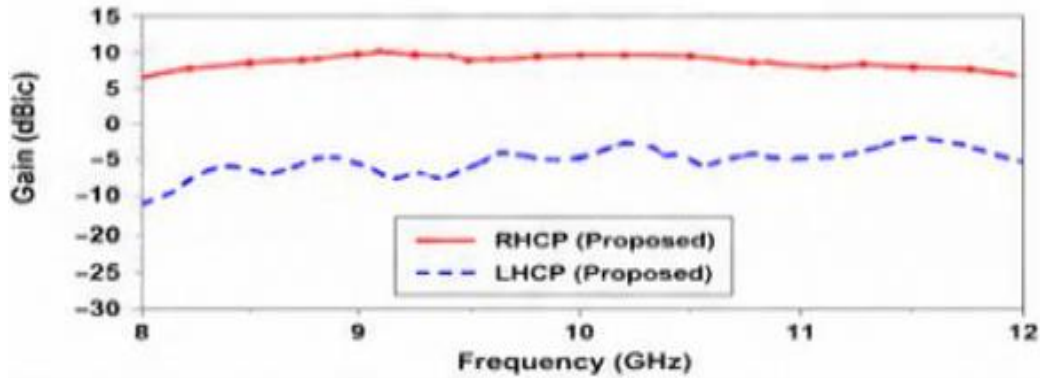


Fig. 14. RHCP / LHCP Comparison.

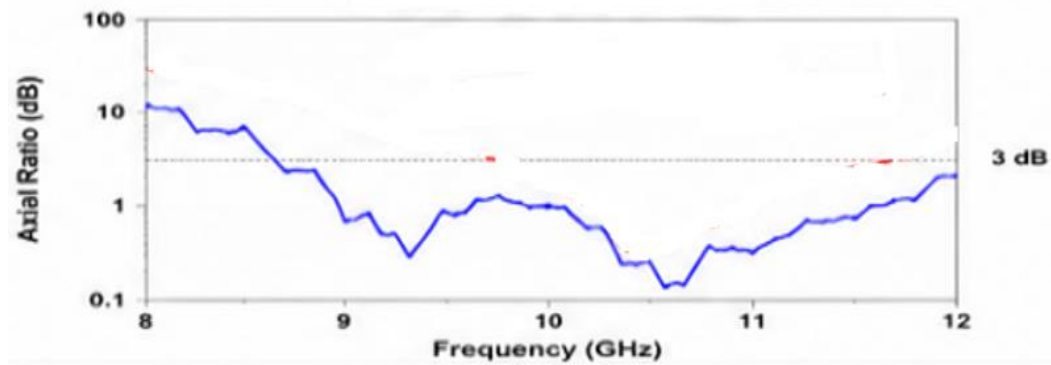


Fig. 15. Axial Ratio vs Frequency.

Furthermore, the simulated 3 dB axial ratio bandwidth spans continuously across 3.3 GHz (8.5 to 11.8 GHz), which easily covers the entire 10 dB impedance bandwidth (9.1 to 10.2 GHz) of the antenna. The deep minimum axial ratio of 0.2 dB at 10.4 GHz indicates near-perfect spatial symmetry and phase quadrature (90° phase shift) between the orthogonal electric field components (E_θ and E_ϕ). The symmetric diagonal corner truncations on the primary patch perturb the surface current path, while the air-gap suspended metamaterial superstrate focuses the broadside radiation without introducing polarization distortion, ensuring robust RHCP purity across the operational X-band frequency range.

IV. CONCLUSION

This paper successfully presented the modelling, design, and performance validation of a high-gain, wideband Right-Hand Circularly Polarized (RHCP) microstrip antenna integrating a 5×5 hybrid metamaterial superstrate, cross-slot Defected Ground Structure (DGS), and HPSO-GA optimization. By combining corner-truncation techniques with DGS loading and an AMC-based metamaterial superstrate array, the proposed architecture overcomes classical microstrip patch limitations. Numerical simulation results confirm that the synthesized antenna achieves an exceptional peak gain ranging between 11.5 and 12.8 dBic, a broad -10 dB impedance

bandwidth (9.1-10.2 GHz), and an outstanding radiation efficiency exceeding 93% across the operational frequency band.

Furthermore, the antenna de and a co-to-cross polarization suppression exceeding 15-20 dB. The integration of cross-slot DGS ensures deep resonance with reflection coefficients dropping below -34 dB, while the HPSO-GA framework guarantees optimal physical dimensions without manual iterative overhead. Excellent inter-port isolation ($S_{21} < -30$ dB) and broadside directional stability make this proposed metamaterial-DGS antenna configuration an ideal monstrates superior polarization purity with a wide 3 dB axial ratio bandwidth spanning 8.5 to 11.8 GHz candidate for modern X-band satellite links, radar tracking, and high-performance wireless communication systems.

REFERENCES

- [1] C.A. Balanis, Antenna Theory: Analysis and Design, 4th ed. Hoboken, NJ, USA: Wiley, 2016.
- [2] D.M. Pozar, Microwave Engineering, 4th ed. Hoboken, NJ, USA: Wiley, 2011.
- [3] R. Garg, P. Bhartia, I. Bahl, and A. Ittipiboon, Microstrip Antenna Design Handbook. Norwood, MA, USA: Artech House, 2001.
- [4] K.F. Lee and W. Chen, Advances in Microstrip and Printed Antennas. New York, NY, USA: Wiley-Interscience, 1997.
- [5] J.R. James and P. S. Hall, Handbook of Microstrip Antennas. London, U.K.: Peter Peregrinus Ltd., 1989.
- [6] N. Engheta and R. W. Ziolkowski, Metamaterials: Physics and Engineering Explorations. Piscataway, NJ, USA: IEEE Press, 2006.
- [7] V. G. Veselago, "The electrodynamics of substances with simultaneously negative values of ϵ and μ ," Soviet Physics Uspekhi, vol. 10, no. 4, pp. 509–514, 1968.
- [8] A. Lai, T. Itoh, and C. Caloz, "Composite right/left-handed transmission line metamaterials," IEEE Microwave Magazine, vol. 5, no. 3, pp. 34–50, Sep. 2004.
- [9] L.H. Weng, Y.C. Guo, X.W. Shi, and X.Q. Chen, "An overview on defected ground structure," Progress In Electromagnetics Research B, vol. 7, pp. 173–189, 2008.
- [10] Y.J. Sung, M. Kim, and Y.S. Kim, "Harmonic suppression with defected ground structure for microstrip patch antenna," IEEE Antennas and Wireless Propagation Letters, vol. 2, pp. 345–347, 2003.
- [11] K.L. Wong, Compact and Broadband Microstrip Antennas. New York, NY, USA: Wiley, 2002.
- [12] J. Kennedy and R. Eberhart, "Particle swarm optimization," in Proceedings of ICNN'95-International Conference on Neural Networks, Perth, WA, Australia, 1995, vol. 4, pp. 1942–1948.
- [13] D.E. Goldberg, Genetic Algorithms in Search, Optimization, and Machine Learning. Reading, MA, USA: Addison Wesley, 1989.
- [14] Ansys High Frequency Simulation Software (HFSS), Version 2023 R1, Ansys Inc., Canonsburg, PA, USA, 2023.
- [15] IEEE Standard for Definitions of Terms for Antennas, IEEE Std 145-2013, pp. 1-80, Mar. 2014.
- [16] G.H. Khouser, S.K.A. Rahim, and M.U. Rahman, "Gain enhancement in microstrip patch antenna with high negative refractive index 3D-metamaterial inspired superstrate for wireless applications," IEEE Access, vol. 12, pp. 7372-7381, 2024.
- [17] H.T. Nguyen, M.T. Le, and Q.N. Tran, "Design of a high-gain X-band electromagnetic band gap microstrip patch antenna for satellite applications," MDPI Electronics, vol. 14, no. 11, p. 2216, May 2025.
- [18] M. Gayathri et al., "Reconfigurable microstrip patch antenna performance improvement using metamaterials and meta-heuristic optimization," Proceedings of the International Conference on Computer Science and Communication Engineering (ICCSCE 2025), Atlantis Press, pp. 1766–1778, Nov. 2025.

AUTHOR'S PROFILE



Mrs. Thana Selvam S., received her Bachelor of Technology (B.Tech) Degree in Electronics and Communication Engineering from Pondicherry Engineering College, Puducherry, India. She is currently pursuing her Master of Technology (M.Tech) Degree in Communication Systems at the Department of Electronics and Communication Engineering, PRIST Deemed University, Thanjavur, Tamil Nadu. Presently, she is working as a Lecturer in the Department of Electronics and Communication Engineering at Women's Engineering College, Puducherry. She has over 18 years of academic and teaching experience, mentoring undergraduate students and guiding course projects in the field of Electronics and Embedded technologies. Her primary research interests include Wireless Communication, VLSI Design, Wearable Patch Antennas, Microprocessor Systems and Digital Signal Processing. She is actively involved in laboratory infrastructure development, curriculum enhancements and professional development programs in advanced electronics engineering.